

**II. Electrostatic Capacity of Glass.***By J. HOPKINSON, D.Sc., M.A.**Communicated by Sir WILLIAM THOMSON, F.R.S.*

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## [PLATE 2.]

1. IN his work on Electricity and Magnetism Professor MAXWELL develops a theory in which electric and magnetic phenomena are explained by changes of position of the medium, the wave motion of which constitutes Light. He deduces with the aid of this theory that that velocity, which is the ratio of the electrostatic and electromagnetic units of electric quantity, is identical with the velocity of light. This deduction may be said to be verified within the limits of error of our knowledge of these quantities. He further finds that the product of the electrostatic capacity and the magnetic permeability of a transparent substance is equal to the square of the refractive index for long waves. The only available experiments for testing this result when Professor MAXWELL's book was published\* were the "Determinations of Electrostatic Capacity of Solid Paraffin," by Messrs. GIBSON and BARCLAY (*Phil. Trans.*, 1871), and the 'Determinations of Refractive Indices of Melted Paraffin,' by Dr. GLADSTONE. Considering the difference in physical state in the two experiments the result verifies the theory fairly well. The various kinds of optical flint glass are suitable for the purpose of making a comparison of refractive indices and specific inductive capacity, since each is an article pretty constant in its composition and physical properties, and has small conductivity and return charge.

2. The only convenient form in which glass can be examined is a plate with plane parallel sides; this plate must form the dielectric of a guard ring condenser. Four instruments are thus required, the guard ring condenser, an adjustable condenser which can be made equal to the first, a battery for giving equal and opposite charges to the two condensers, and an electroscope to show when the added charges of the condensers are nil.

*Guard Ring Condenser.*—Fig. (1) represents the guard ring condenser in elevation;

\* Since then determinations have been made by BOLTZMANN for paraffin, colophonium, and sulphur (*Pogg. Annalen*, 1874, vol. cl. pp. 482 and 531, and vol. cliii. p. 525), and for various gases (*Pogg. Ann.*, 1875, vol. clv. p. 403), by SILOW for oil of turpentine and petroleum (*Pogg. Ann.*, 1875, vol. clvi. p. 389, and 1876, vol. clviii. p. 306), and by SCHILLER (*Pogg. Ann.*, 1874, vol. clii. p. 535) and WÜLLNER (*Pogg. Ann.*, 1877, new series, vol. i. pp. 247, 361) for plate glass.

fig. (2) in plan through  $h\ h$ . It consists essentially of an insulated brass disc  $k$  surrounded by a flat ring  $h\ h$ , and covered by a brass shield connected with  $h\ h$ . It is opposed by a larger disc  $e\ e$  parallel with  $k$  and  $h\ h$ , which is always connected to the case of the electrometer. The disc  $k$  and ring  $h\ h$  are connected, simultaneously charged, next separated, and then at one moment  $h$  is put to earth, and  $k$  discharged in such manner as the experiment may require.

$a\ b$  and  $c\ d$  are triangular pieces of iron forming with three wrought-iron stays a stiff frame. To the tops of these stays are screwed three legs of ebonite  $g\ g$ , which serve to support and insulate the guard ring  $h\ h$ . The disc  $e\ e$  is of brass truly turned, it is carried on a stem which is screwed for a portion of its length with exactly 25 threads to the inch, a motion parallel to itself is secured by bearings in each frame plate; these are not ordinary round bearings which may work loose, but are of the form represented full size in fig. 3.  $e\ e$  is prevented from rotating by a pin working through a hole in the upper triangular plate and pressed against one side of the hole by a steel spring. The plate  $e\ e$  is raised or lowered by a milled nut  $f$ , divided on the circumference into 100 parts, and bearing upon a piece of brass tubing secured to the lower plate of the frame.  $k$  is carried by two rods of ebonite  $l\ l$ , which insulate it from  $h\ h$ ; both were faced in the lathe together so as to be truly in one plane. The diameter of the disc  $k$  is 150 millims., it is separated from the ring by a space of 1 millim. When the capacity of a glass plate is to be measured a dish of pumice and sulphuric acid is placed upon the disc  $k$  between the rods  $l\ l$ , and a second dish upon the triangular plate  $c\ d$ , the whole instrument being loosely surrounded by a glass cylinder. This instrument also serves to measure with sufficient accuracy the thickness of the glass plates. To ascertain when the plates are in contact, or when the glass plate to be measured is in contact with  $h\ k\ h$ , slips of tissue paper are interposed between the ebonite legs  $g\ g$  and the plate  $h\ h$ , and the contact is judged by these slips becoming loose, a reading being taken for each slip.

The sliding condenser was the identical instrument used by GIBSON and BARCLAY, kindly lent to the author by Sir W. THOMSON; it was used simply as a variable condenser. Although a more finely graduated instrument than the guard ring condenser, it was not used as a measuring instrument, because its zero readings had to be valued by the guard ring condenser; it seemed better to use it like the counterpoise in the system of double weighing, adjusting it to the guard ring condenser with the glass in, then removing the glass and adjusting the guard ring condenser to equality with the sliding condenser. It suffices to say that the sliding condenser has two adjustments, a fine one denoted here by  $S_1$ , and a coarse one denoted by  $S_2$ .

The electroscope was Sir W. THOMSON's quadrant electrometer adjusted for maximum sensibility and charged as highly as it would stand. A single DANIELL'S element gave from 120 to 160 divisions of the scale.

*The battery* consisted of 48 or of 72 DANIELL's elements of a very simple construction; a piece of copper wire covered with gutta percha is stripped for a short distance at each end, it is set in a test tube 6 or 7 inches long, a piece of zinc being soldered to its upper extremity. Some sulphate of copper in powder is put in the tube around the exposed wire, this is covered by a thick plug of plaster of Paris, and the element completed by the addition of dilute zinc sulphate solution, into which the zinc which is soldered to the wire of the next element dips. The element has a very high resistance, but that is of no consequence for electrostatic experiments. The middle of the series is put to earth. The battery thus gives the means of charging two condensers to equal but opposite potentials. The poles of the battery are connected with the switch through the electrometer reversing key. In each case two experiments are made, one in which the guard ring is positive, in the other negative.

*The switch* is represented in plan in fig. 4, and its place is indicated in elevation in fig. 1. Calling the poles of the battery A and B, its purpose is to make rapidly the following changes of connection:—

- (1.) A, sliding condenser; B, guard ring, disc *k*; earth, quadrant of electrometer.
- (2.) A, B, guard ring, earth; disc *k*, sliding condenser.
- (3.) To connect the disc *k* and the sliding condenser to the quadrant of the electrometer.

The combination (1) may exist for any time long or short, but (3) follows (2) within a fraction of a second, and the observation of the electroscope consists in deciding whether or not the image moves *at the instant* of combination (3), and, if it moves, in which direction. In (2) the poles of the battery are put to earth, in order that one may be sure that the parts of the switch with which they are connected do not disturb the result by inductive action on the parts connected with the condensers.

*q q* is a plate of ebonite screwed to the shielding cover of the condenser, *r* is a steel spring connected to earth, *s* a similar steel spring connected to one pole of the battery.

*t v* are segments of brass of which the securing screws pass through to the brass cover.

*w u*, similar segments insulated from the brass cover and guard ring, connected respectively to the sliding condenser and the electrometer.

*p* is an ebonite handle and brass pin which turns in an insulated brass socket connected by a spring *m* with the disc *k*; *p* carries a piece of ebonite *x x* which moves the springs *r s* from contact with *t v* to contact with *u w*, and also a spring *y y* which may connect *t v* with the disc *k*, or, when turned into the position indicated, *w* with the disc *k*, and instantly after both with the electrometer. One pole of the battery is always connected to the guard *h h*. The switch is protected against inductive action from the hand of the observer, or from electrification of the top of the ebonite handle when touched with the finger by a copper shield *n n* connected with the guard ring through the cover.

The guard ring screw reading is denoted by R. R (+) when the guard ring is positive, R (-) when it is negative. This condenser must be regarded as a circular plate of 151 millims. diameter with a uniform distribution of electricity on its under surface; its capacity is therefore  $\frac{140 \cdot 3}{x}$  centimetres where  $x = R -$  the reading when  $k$  and  $e e$  are in contact.

3. In order to ascertain the distance between the plates from the screw reading R, it is necessary to know the reading when the plates  $k h h$  and  $e e$  are in contact. Slips of thin tissue paper are introduced at the top of each of the ebonite legs, the lower plate is raised, and a reading is made when each slip becomes loose; the mean of the three readings may be taken as the zero when the instrument is used to measure the thickness of plates, or when  $h k h$  is carried by an interposed plate, but it will require a correction when in the subsequent measurements the upper plate is carried by the ebonite supports only, for the upper plate must have been lifted by a greater or less amount depending on the compression of the paper slips and on the imperfect rigidity of the brass before the slips can be released. The amount of this correction was estimated in two different ways.

1st. Everything on the upper plate was connected with one pole of the battery and also with the electrometer. The plates were brought to contact; it was found the slips became loose at 1·15, 1·13, 1·09, mean 1·12, the lower plate was very slowly lowered until the upper plate became insulated, as declared by the movement of the image on the electrometer scale. This occurred at 1·22, indicating a correction of 0·10.

2nd. A plate of light flint glass was introduced between the condenser plates; the slips were just loose at readings—

16·15      16·16      16·11.      Mean 16·14.

The two condensers were now connected through the switch and rendered equal, the screw being turned to vary the distance of the plates, and the slide being adjusted to make the sliding condenser equal to the guard ring. The following corresponding pairs of readings were obtained :—

R 16·10	16·20	16·30	16·25	16·40
S <sub>1</sub> 180	180	150	170	100
R 16·30	16·27	16·24	16·20	16·17
S <sub>1</sub> 150	170	180	180	185

It thus appears that the capacity of the guard ring condenser does not begin to diminish till R is between 16·24 and 16·27. This indicates a correction between 0·10 and 0·13. Throughout the experiments a correction of 0·10 is used whenever the upper plate is carried by the ebonite legs alone.

4. The glasses examined were CHANCE'S *optical light flint*, *double extra dense flint*, *dense flint*, *a special light flint*, and a piece of common plate glass.

*Light flint*, density about 3·2.

Two plates were examined of different thickness, the plates were also from different meltings of glass made at different times, and may be regarded as two quite independent samples of glasses intended to be of the same composition.

A. Thickness, 15·01 turns of the screw; diameter, 220 millims.

First Experiment.—Plates of guard ring condenser in contact with glass plate. 48 elements in the battery.

$$\begin{aligned} S_2 = 0 & \quad S_1 = 50 \text{ when sliding condenser positive.} \\ & = 20 \quad " \quad " \quad \text{negative.} \\ \text{Mean} = 35 & \end{aligned}$$

It is found that  $S_2 = 0$ ,  $S_1 = 35$  is equal to the guard ring condenser with the glass plate out, when the distance between the plates is 2·18 turns of screw,

$$\text{Hence } K = 6\cdot89.$$

Second Experiment.—Battery of 72 elements.

$$\begin{aligned} S_2 \text{ drawn out beyond the graduation, } S_1 = 160 \text{ when slide is positive.} \\ & = 220 \quad " \quad \text{negative.} \\ \text{Mean} = 190 & \end{aligned}$$

Glass plate removed.

$$S_1 = 190 \quad R (+) = 3\cdot50 \quad R (-) = 3\cdot43.$$

Mean reading for contact of plates 1·14, when corrected 1·24.

So plate of glass 15·01 is equal to plate of air 2·225,

$$\text{Hence } K = 6\cdot76.$$

B. Thickness, 10·75 turns of screw; diameter, 220 millims.

Plates of guard ring both in contact with glass, battery of 72 elements.

$$\begin{aligned} S_2 = 25 \quad S_1 = 450 \text{ when positive.} \\ & = 400 \text{ when negative.} \end{aligned}$$

Glass plate removed.

$$\begin{aligned} S_1 = 425 \text{ equivalent to } R (+) = 2\cdot85 \\ & R (-) = 2\cdot80 \end{aligned}$$

or plate of glass 10·75 equal to air 1·585.

$$K = 6\cdot90.$$

Mean of three determinations—

$$6\cdot85.$$

“*Double extra dense flint glass*,” or “*Triple dense flint*,” density about 4·5.

Thickness of plate, 24·27 turns; diameter, 235 millims.

First Experiment.—Plates in contact with glass. 48 elements in battery.

$$S_2 \text{ drawn out, } S_1 = 95.$$

Plate removed, condensers again equal when  $R = 3.60$ .

$$\text{Hence } K = 10.28.$$

Second Experiment.—Plates in contact with glass. 72 elements in battery.

$$S_2 \text{ drawn out, } S_1 = 55 \text{ when slide is positive.}$$

$$= 95 \quad , \quad \text{negative.}$$

$$S_1 = 75 \text{ is equivalent to } R(-) = 3.61$$

$$R(+) = 3.69$$

$$K = 10.07.$$

The latter result is probably much the best; take 10.1 as most probable value.

In the next two glasses the determinations were made first with plates in contact with glass, second with a space of air between the glass and the upper plate; the results suggested the experiments of § 3. In each case 72 elements were used.

*Dense flint* (the glass generally used in the objectives of telescopes).—Density about 3.66, thickness = 16.58 turns of the screw, diameter = 230 millims.

First Experiment.—Plates in contact with glass,  $S_2$  drawn out.

When the slide is positive,  $S_1 = 205$ , on removal of glass plate this equals  $R(-) = 5.50$ . When the slide is negative,  $S_1 = 175$ , on removal of glass plate  $R(+) = 3.50$ .

$$\text{Hence } K = 7.34.$$

The mean zero reading being now 1.15.

Second Experiment.— $R$  is put at 18.14 with glass between the plates.

$S_2$  drawn out when the slide is negative.

$S_1 = 10$  on removing glass equals  $R(+)$  3.78, when the slide is positive.

$S_2 = 40$  on removing glass equals  $R(-)$  3.79, i.e. glass 16.58 and air 0.32 are equivalent to air 2.525 or  $K = 7.45$ .

$$\text{Mean} = 7.4.$$

*A very light flint*.—Density about 2.87, thickness = 12.7 turns of the screw, diameter = 235 millims.

First Experiment.—Plates in contact with glass  $S_2$  drawn out, when the slide is negative.

$S_1 = 380$  on removing glass equals  $R(+)$  3.20, when the slide is positive.

$S_1 = 440$  on removing glass equals  $R(-)$  3.18.

$$K = 6.6.$$

Second Experiment.— $R$  was put at 14.50,  $S_2$  was drawn out when the slide is positive.

$S_1 = 80$  on removing glass equal to  $R(-)$  3.71, when the slide is negative.

$S_1=50$  on removing glass equal to  $R (+) 3\cdot72$ , so glass 12·70 and air 0·55 is equivalent to air 2·475.

$$K=6\cdot55.$$

$$\text{Mean}=6\cdot57.$$

An attempt was made to determine  $K$  for a piece of plate glass; the considerable final conductivity of the glass caused no serious inconvenience, but the very great development of that polarization on which residual charge depends produced a condenser in which the capacity seemed to increase very rapidly indeed during a second or so after making connexions; this effect could not be entirely separated from the instantaneous capacity, a value  $K=7$  was obtained, but it was quite certain that a considerable part of this took time to develop.

5. The repetition of the experiment in each case gives some notion of the probable error of the preceding experiments. Something must be added for the uncertainty of the contact reading. It will perhaps not be rash to assume the results to be true within 2 per cent.

Since the magnetic permeability cannot be supposed to be much less than unity, it follows that these experiments by no means verify the theoretical result obtained by Professor MAXWELL, but it should not be inferred that his theory in its *more general* characters is disproved.

If the electrostatic capacities be divided by the density, we find the following quotients :—

	$\rho$	$K$	$\frac{K}{\rho}$	$\mu$ (index of refraction for line D)
Light flint . . . . .	3·2	6·85	2·14	1·574
Double extra dense . . . .	4·5	10·1	2·25	1·710
Dense flint . . . . .	3·66	7·4	2·02	1·622
Very light flint . . . . .	2·87	6·57	2·29	1·541

Thus  $\frac{K}{\rho}$  is not vastly different from a constant quantity. Messrs. GIBSON and BARCLAY find  $K$  for paraffin 1·977; taking the density of paraffin as 0·93, we have the quotient 2·13. This empirical result cannot of course be generally true, or the capacity of a substance of small density would be less than unity.

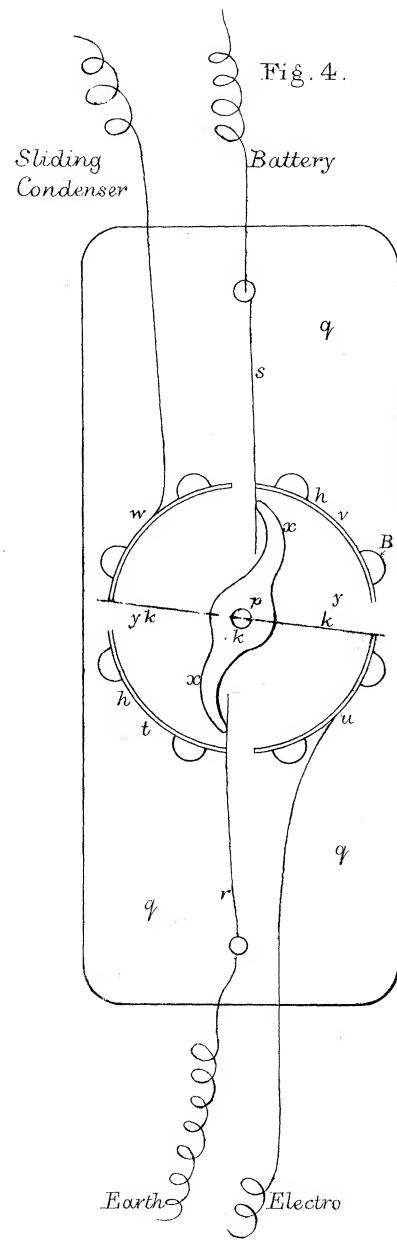
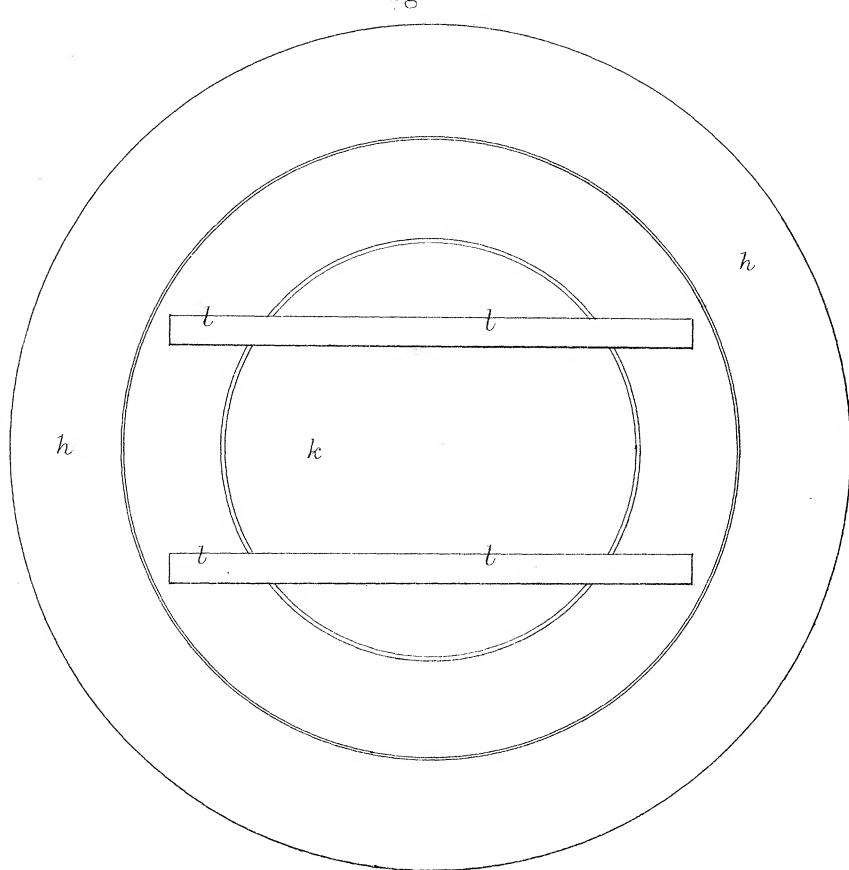
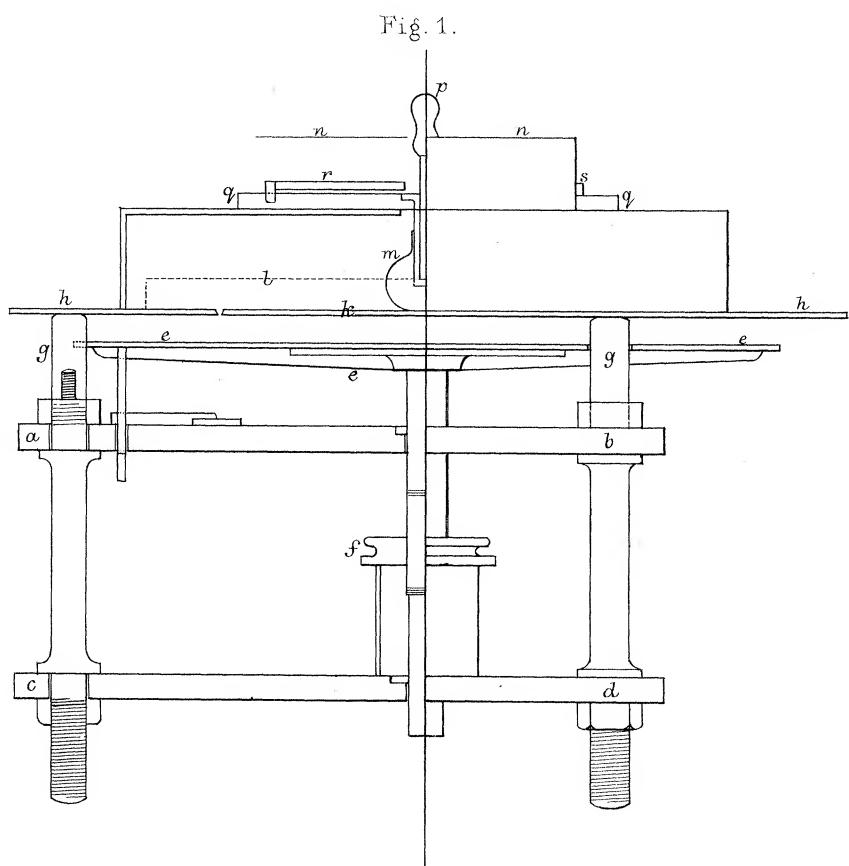


Fig. 3.

